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"NUMERICAL STUDY ON THE EFFECT OF CONTRACTION RATIO ON SUPERSONIC INTAKE STARTING CHARACTERISTICS"

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ABSTRACT

Supersonic/Hypersonic air intake performance is defined in terms of intake capability and efficiency. This work mainly deals with an intake starting characteristic for different contraction ratio of hypersonic vehicles. The strong-shock design principle is proposed on the basis of comparison of the limiting contraction line with the Kantrowitz (self-starting) lines of a few particular ramp intakes. Our study is based on varying area contraction ratio (1, 1.5, 1.7, 2 and 2.5) and to find the best performance of intake starting condition for both symmetry (2D) and axisymmetric (3D) for various Mach numbers. During research work, we found that intake starting problem for symmetry to axisymmetric is not same, it may start in axis symmetric whereas in symmetry, it may lead to unstart. This paper represents the study on different area ratio configuration for start flow in the air intake.

KEYWORDS: Intake Starting Characteristic, Contraction Ratios, Intake Un-Start & Axi-Symmetry Vs Symmetry Intake

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Original Article

INTRODUCTION

An air breathing propulsion system is designed to suck the air, compress it to the required pressure and add heat to deliver require thrust. Currently many countries are focused on Supersonic and Hypersonic air breathing technology such as Ramjet and Scramjet engines. In such engines, air intake plays crucial role for heat addition in the combustor. Intakes of Ramjets are designed such that it would bring down the high speed compression of incoming air for efficient to subsonic level before entering the combustion chamber. High stagnation temperatures took place due to such speed reduction. Varying geometry may not be an option for inlet designers because of mechanism and difficulties. It is essential to have a converging duct to decelerate the incoming air to compress airflow and supply the compressed air into the combustor chamber.

This engine can carry two distinctly different flow configurations for same Mach number. There are different conditions to operate intake to start. When bow shock stands in front of intake, it is known as sub critical conditions, where the inlet's internal flow is sub-sonic, remaining flow will divert overboard. The second possible flow has no bow shock, no overboard spillage and is supersonic throughout. This is known as supercritical condition. The intake must be started to obtain an efficient operation of engine which obtains by steady supersonic flow in the intake decelerating towards its exit. Heavy loss in total pressure and mass flow leads to un-started condition. Starting condition requires the oblique shock during hypersonic/supersonic flow throughout the

converging portion of the inlet. There are several ways to start an inlet, including such traditional quasi-steady techniques as over speeding, using of variable geometry, overboard spillage, mass spillage via inlet wall perforations, as well as some new techniques employing an unsteady effect. More recently, a quasi-steady theory for prediction of flow starting in perforated inlets was developed [1].

NUMERICAL THEORY

The quasi-one-dimensional Kantrowitz theory [1], of intake starting is based on two main assumptions:

- The intake is fully enclosed, which means free stream velocity is normal to the entry plane.
- The flow is quasi-steady condition; where the freestream velocity varies too slow in mean time the flow tries to adjust itself to the variation.

Under these assumptions the Kantrowitz theory leads to three distinct regions on the intake-area-ratio/freestream-Mach-number diagram. Below the isentropic curve, steady supersonic adiabatic flow in the intake (i.e., started flow) is not possible because its existence would require a decrease in entropy or, in other words, such a steady flow would pass through the area less than its sonic (critical) area. In this region, the only steady solution is the non starter one. Bow shock in front of the intake necessitates partial overboard spillage; flow throughout the intake is subsonic [1].

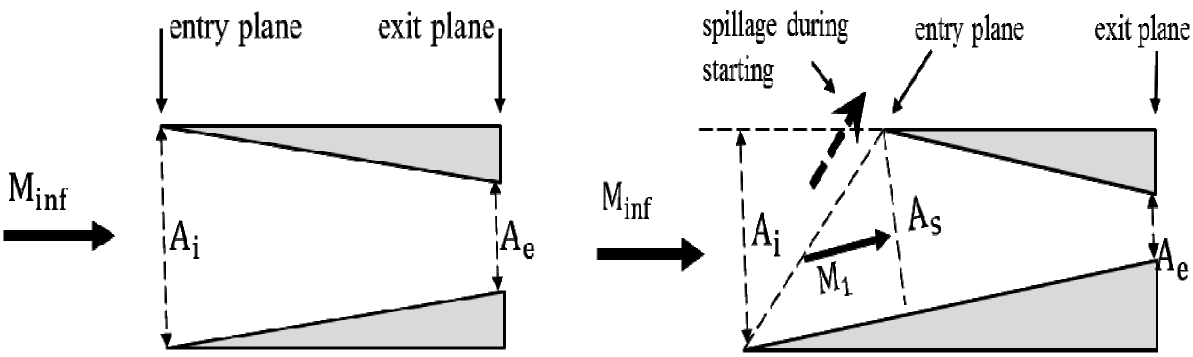

Figure 1: Air Intake for Fully Closed and Overboard Spillage.

It is proposed to use unsteady effects, thus circumventing the Kantrowitz limitations. It is demonstrated that an intake can be started using high intake-acceleration values when the induced flow is no longer quasi-steady. Another interesting option suggested is to attain intake-starting by inducing unsteady flow in the intake by rupturing strategically placed diaphragms. Both of these techniques rely on unsteady flow to circumvent the area-ratio limitation imposed by the Kantrowitz quasi-steady theory [1].

The following geometrical relation can be written for such intakes:

$$\frac{A_e}{A_i} = \frac{A_e}{A_S}\frac{\sin(\sigma_1 - \delta_1)}{\sin\sigma_1} \tag{1}$$

The deflection angle δ_1 is determined from the shock angle with the oblique shock relation σ_1 for a perfect gas:

$$\tan\delta_1 = \frac{(M_\infty^2 \sin^2\sigma_1 - 1)\cot\sigma_1}{\left[\frac{\gamma+1}{2}\right] M_\infty^2 - M_\infty^2 \sin^2\sigma_1 + 1} \qquad (2)$$

The shock Mach number M_1 after the oblique shock is calculated as follows:

$$M_1^2 = \frac{1}{\sin^2(\sigma_1 - \delta_1)} \times \frac{2 + (\gamma - 1)M_\infty^2 \sin^2\sigma_1}{2\gamma M_\infty^2 \sin^2\sigma_1 - (\gamma - 1)} \qquad (3)$$

The first step in the determination of the limiting contraction value for an intake to be started, by overboard spillage effect alone, is to establish the external and internal compression sections fig 3. For the preceding ramp intake, the free stream flow, processed by the attached weak oblique shock, is directed along the ramp surface. The internal compression (or fully enclosed) intake section begins from the aforementioned normal line issued from the cowl leading edge. According to the quasi-one-dimensional Kantrowitz theory, flow in the internal compression section starts spontaneously if its area ratio $A_e = A_s$ is equal to or higher than the following *K* value, determined with the Mach number M_1 [1].

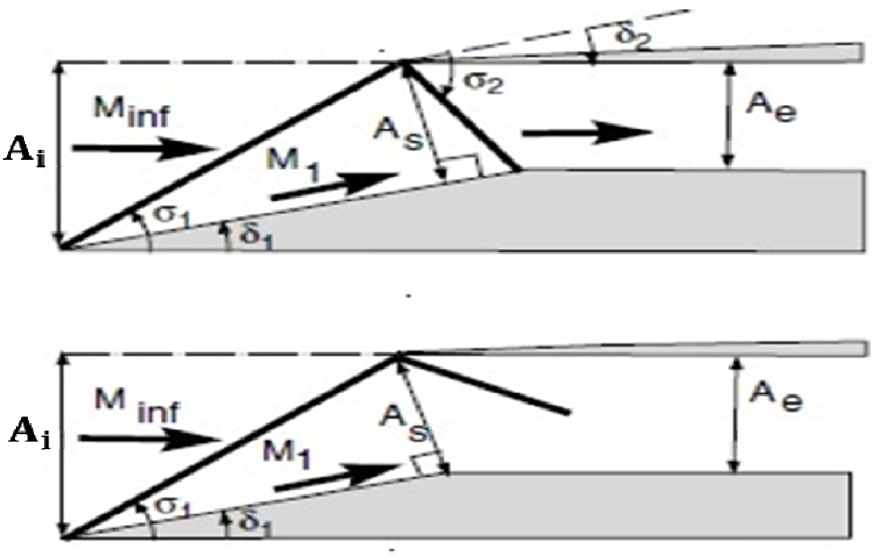

Figure 2: Intake Area Ratio/Free stream Mach Number [1].

$$\left(\frac{A_e}{A_s}\right)_k = \left[\frac{\gamma - 1}{\gamma + 1} + \frac{2}{(\gamma + 1)M_1{}^2}\right]^{\frac{1}{2}} \left[\frac{2\gamma}{\gamma + 1} - \frac{\gamma - 1}{(\gamma + 1)M_1{}^2}\right]^{\frac{1}{\gamma - 1}} \qquad (4)$$

INTAKE STARTING CONDITIONS

One of the major design considerations for the intake is its design for starting. Intake starting is defined as the ability of the intake to let through it, the designed mass flow rate when the air breathing operation starts. It is a function of the flight Mach number, altitude and the intake area ratio defined as the area to the throat area. For 2-D intakes the contraction ratio (Ratio of inlet to throat area) as function of inlet Mach number is given in fig 4 known as Kantrowitz limit. This curve defines the ratio below which the intake will start automatically. We can also see the experimental results for 3-D type of

intake for automatic starting.

The contraction ratio of the intake is an important parameter for the intake design. Increase in contraction ratio increases the compression and hence the combustor entry pressure which is favourable for combustion and also increases the combustion efficiency. On the other hand, an increase in this ratio will tend to unstart the intake, which in turn causes the engine to shut down.

The initial design methodology is to design with the contraction ratio within the starting range provided in fig 4. If the required compression is not met with this ratio, the contraction ratio will be increased with provisions to mitigate unstart.

Unstart mitigation options:

- Introducing bleed to temporarily increase flow through the intake.
- Providing a movable intake cowl to reduce the entry area during air breathing takeover

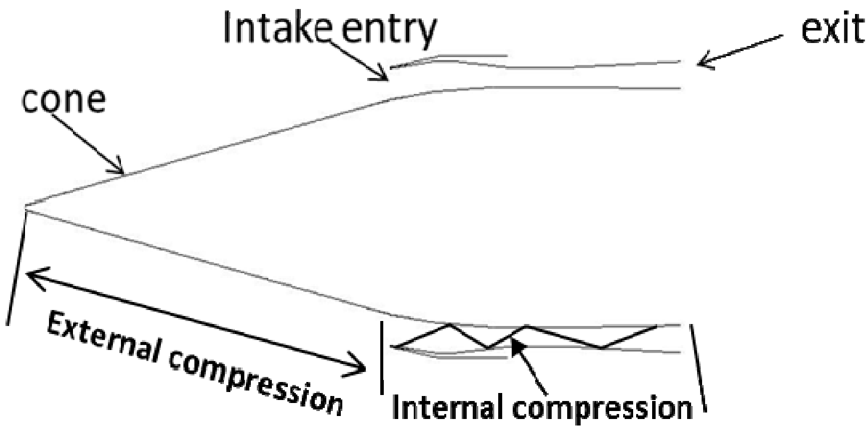

Figure 3: Geometrical View of Air-Intake.

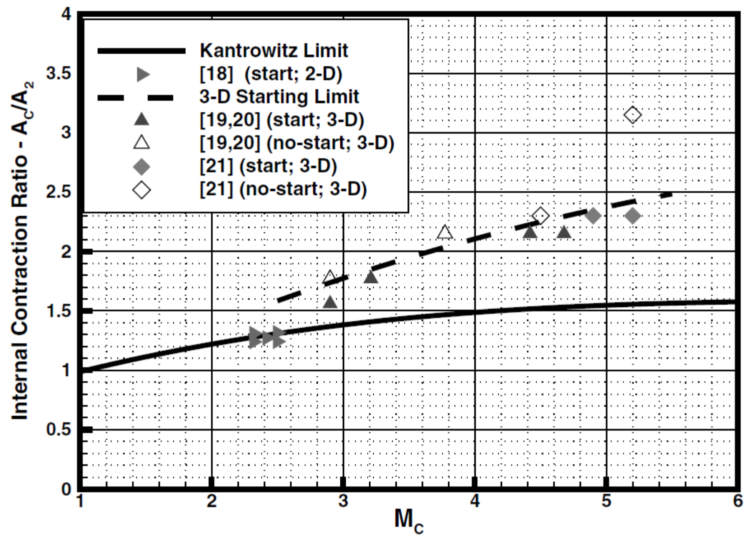

Figure 4: Kantrowitz Graph (Contraction Ratio For Intake Starting).

INTAKE UNSTART

Unstart of the intake could occur due to several reasons which are

- Over contraction
- Variation of flight conditions
- Perturbations in combustor operation
- Back pressure
- Angle of attack, etc.,

Or due to a combined effect of these factors

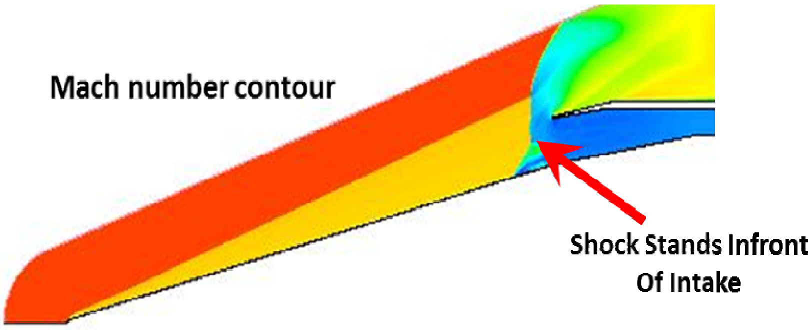

Figure 5: Intake Unstart.

GEOMETRY AND GRID

In this study, we are generating a model with various Area ratio (A_e/A_t=1, 1.5, 1.7, 2 and 2.5) without changing the cowl. We are generating sufficient flow for starting conditions. We are performing our study on both symmetry and axisymmetric conditions, so that we can study the design of air intake based on the requirement. Grid independence study is performed to reduce the computational cost. For this, we generated mesh of coarser, medium and fine with 0.03M, 0.07M and 0.15M node points respectively. Y+ value for this simulation is one (Y+~1).

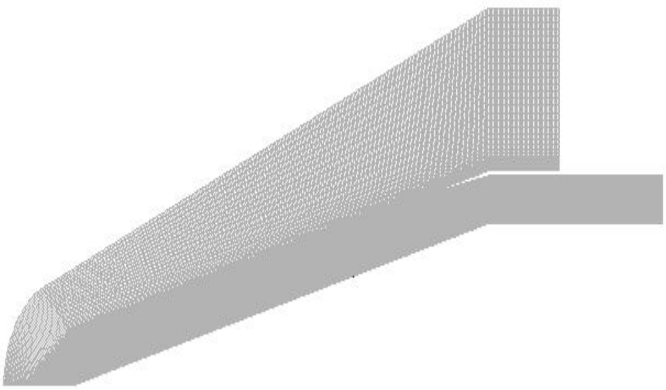

Figure 6(a): Air-Intake with Domain

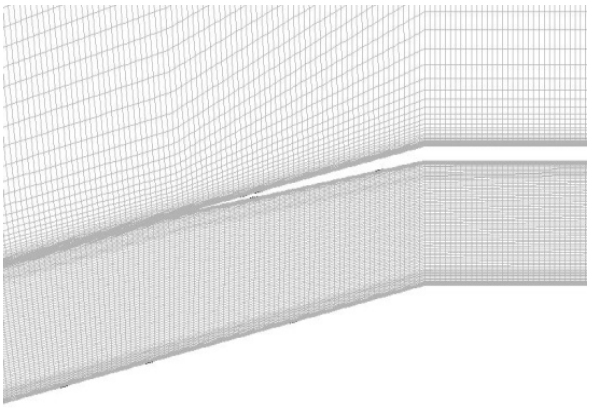

Figure 6(B): Zoom View at Intake Entry

Figure 6:Grid Points.

SIMULATION METHODOLOGY

In this study, the commercial CFD package fluent is used for the flow within domain. To simulate on the computational

requirement, only half the geometry is considered and symmetry conditions are assumed. The computational grid, which is generated with the ANYS ICEM CFD and only structured mesh is used. The steady flow simulation is performed by using the density based solver. Air is assumed to have the properties of an ideal gas.

Concerning the boundary conditions, the domain has boundary types which are named for this simulation is far, far-outlet, intake-bottom-wall, intake-top-wall, nose-cone, outlet and symmetry. In this boundary type, pressure-far-field as inlet and pressure-outlet as for outlet and the remaining as standard wall conditions are taken. Turbulence model used for this analysis is k-omega shear stress transport (SST) with standard values.

FLOW CONDITIONS

The free stream conditions are M= (2 to 6), P=0.131atm, and T=205.65 K, at an operating altitude of 15km above sea level. Intake exit pressure is assumed to be ambient. This results in the inlet being located in the dual solution zone, between the isentropic and the Kantrowitz criterion, as per Figure 4.

RESULTS AND DISCUSSIONS

In this study, we are discussing about wedge shock and conical shock performance and effects caused by it. Wedge shock is simulated in 2D planar, whereas conical shock is simulated as axisymmetric, which will be assumed as 3D. Air intake is designed based on the entry Mach number which comes from wedge or cone shock that is same for both conditions. Shock on lip is designed for axisymmetric condition, where the conical shock hit to the intake cowl lip that is designed condition where maximum flow rate allows into the system. The area is taken for axisymmetric to find the area ratios but whereas in 2D planar height ratios are taken and both ratios kept same for better understanding of both conditions. Intake is tested at different Mach numbers - M2, M3, M4, M5 and M6 for symmetry and axisymmetric. The results are shown in this paper is only M5 condition so as to compare the effects between symmetry and axisymmetric conditions.

For $AR = 1$

For Area ratio 1, we obtained self-start condition for both 2D planar and 2D axisymmetric. As we see for 2D wedge shock (i.e. Oblique shock) is away from the cowl. Whereas 2D axisymmetric the conical shock is hitting on the cowl lip. Results 2D (symmetry) vs 3D (axisymmetric) where satisfied with the kantrowitz theory that is shown in figure 4.

For 2D: Symmetry Condition

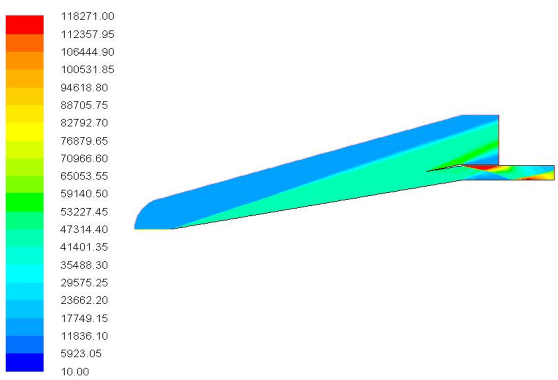

Figure 7 (a): Static Pressure

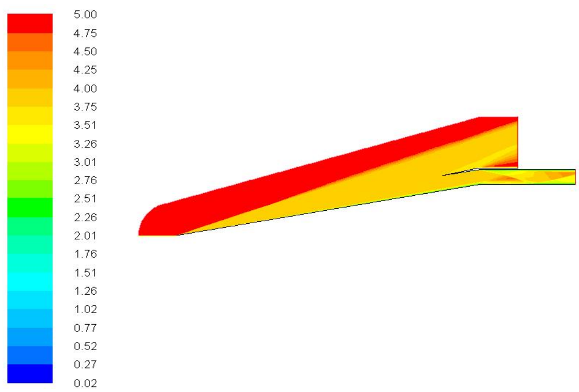

Figure 7 (b): Mach Number

Figure 7: 2D planar HR-1, M=5 Condition

For 2D: Axisymmetric Condition

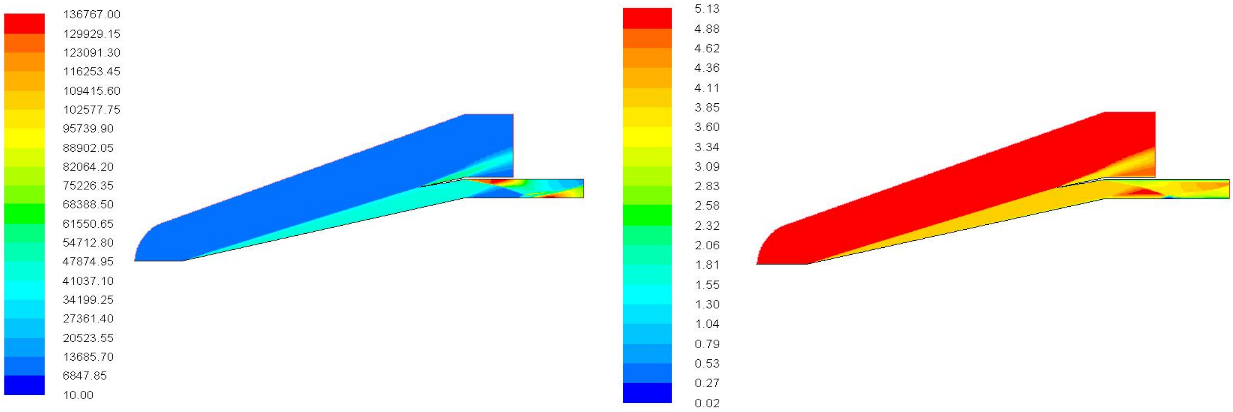

Figure 8(a): Static Pressure **Figure 8(b): Mach Number**

Figure 8: 2D Axisymmetric AR-1, M=5.

For AR = 1.5

For 2D: Symmetry Condition

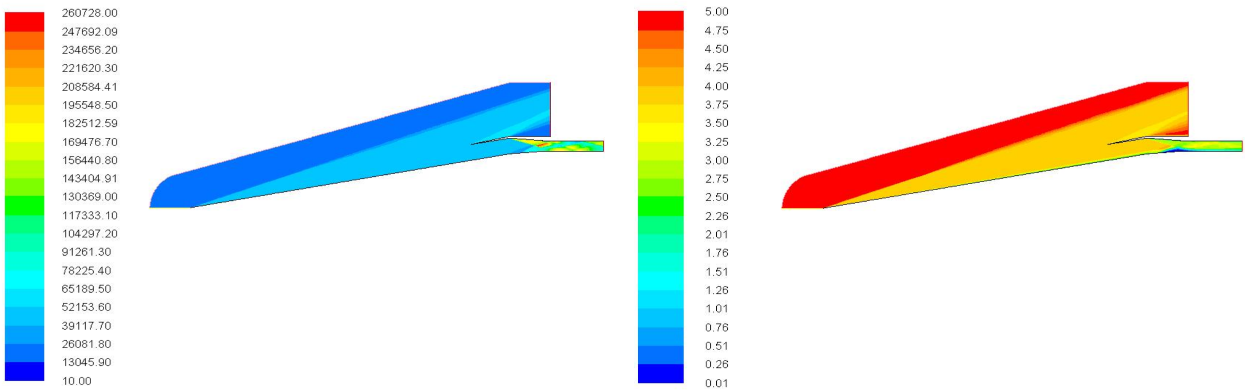

Figure 9 (a): Static Pressure **Figure 9 (b): Mach Number**

Figure 9: 2D planar HR-1.5, M=5

For 2D Axisymmetric Condition

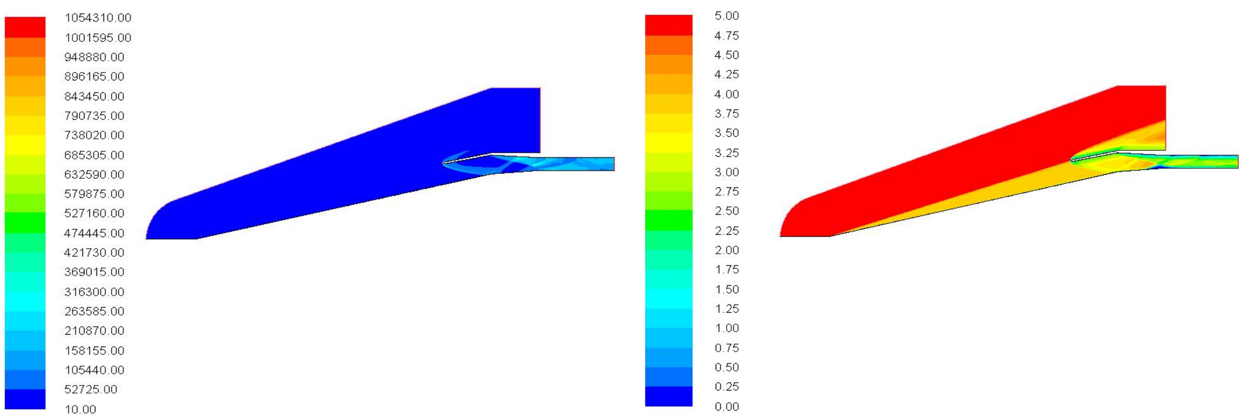

Figure 10 (a): Static Pressure **Figure 10 (b): Mach Number**

Figure 10: 2D axisymmetric AR-1.5, M=5

For **AR = 1.7**

For 2D: Symmetry Condition

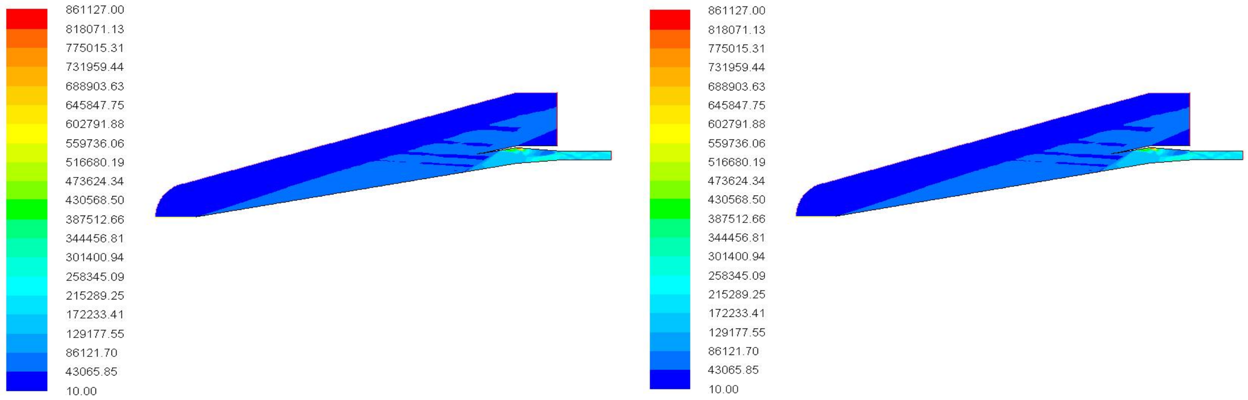

Figure 11 (a): Static Pressure **Figure 11 (b): Mach Number**

Figure 11:2D Planar HR-1.7, M=5

For 2D: Axisymmetric Condition

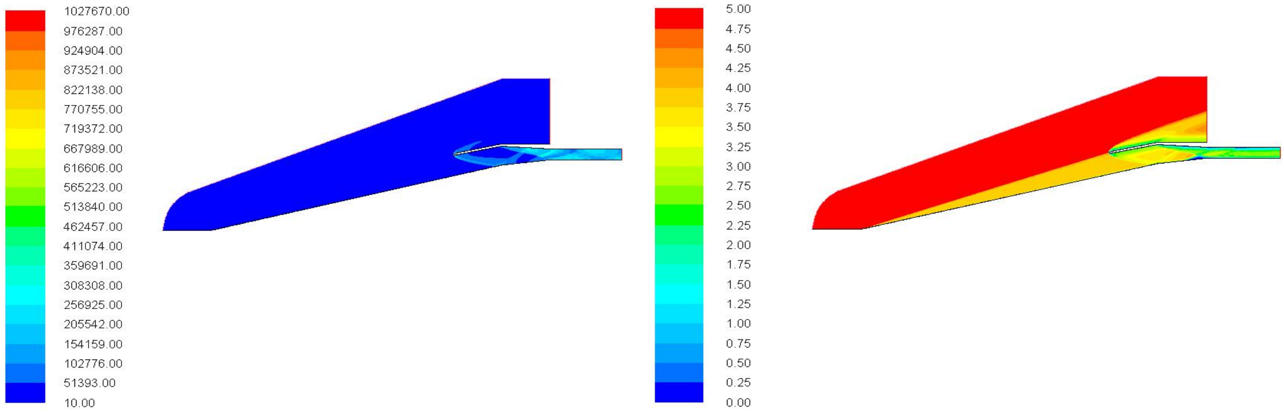

Figure 12 (a): Static Pressure **Figure 12 (b): Mach Number**

Figure 12: 2D axisymmetric AR-1.7, M=5

For **AR = 2**

For 2D: Symmetry Condition

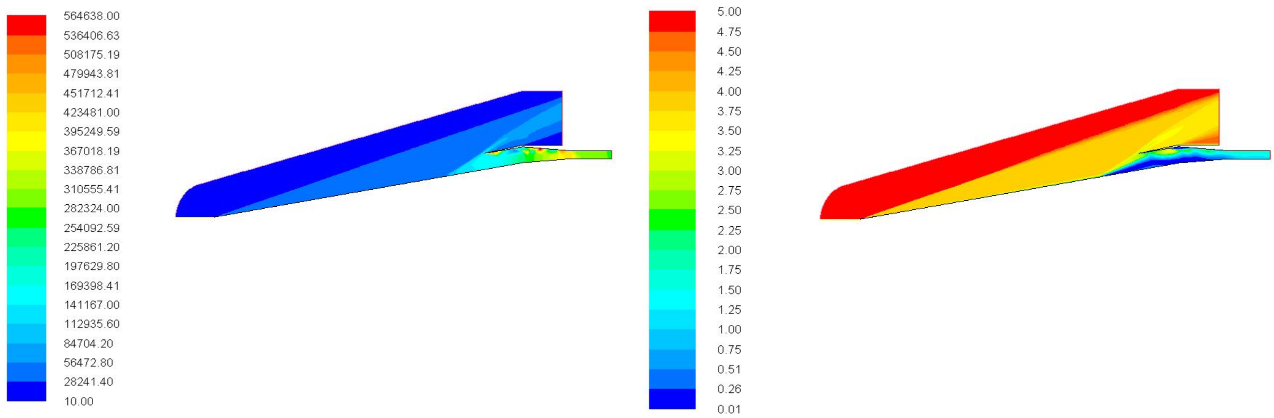

Figure 13 (a): Static Pressure **Figure 13 (b): Mach Number**

Figure 13: 2D planar HR-2, M=5

For 2D: Axisymmetric Condition

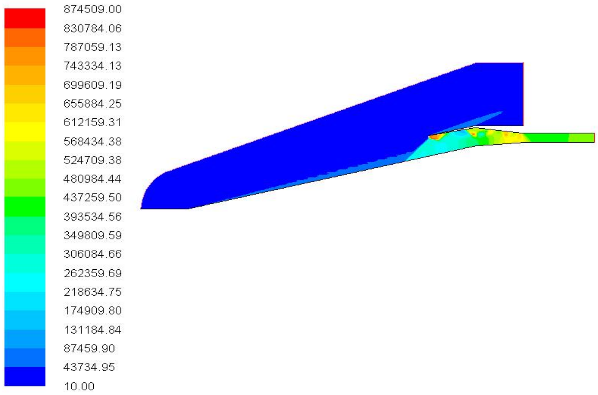

Figure 14 (a): Static Pressure

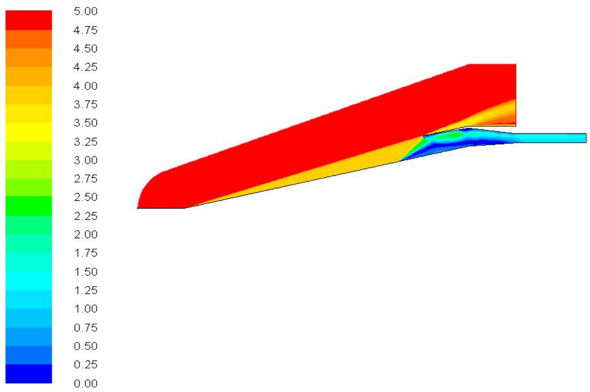

Figure 14 (b): Mach Number

Figure 14: 2D axisymmetric AR-2, M=5

For **AR = 2.5**

For 2d: Symmetry Condition

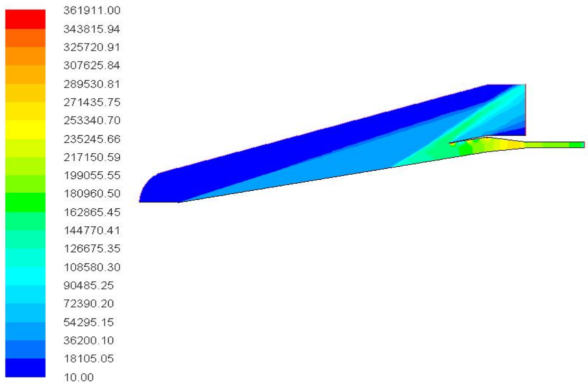

Figure 15 (a): Static Pressure

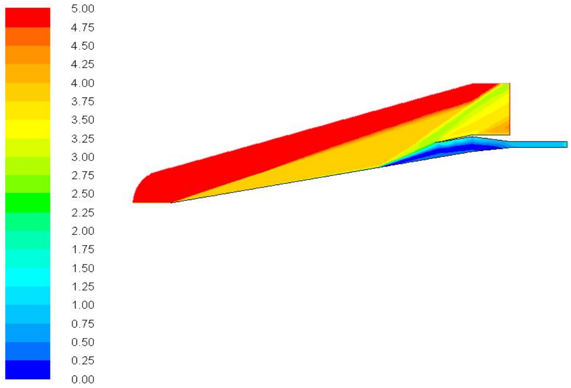

Figure 15 (b): Mach Number

Figure 15: 2d Planar Hr-2.5, M=5

For 2D Axisymmetric Condition

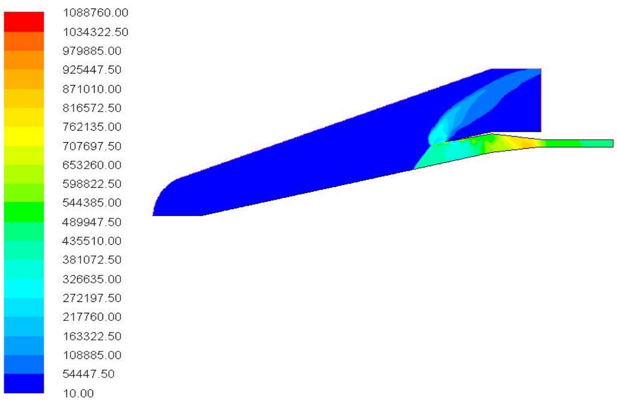

Figure 16 (a): Static Pressure

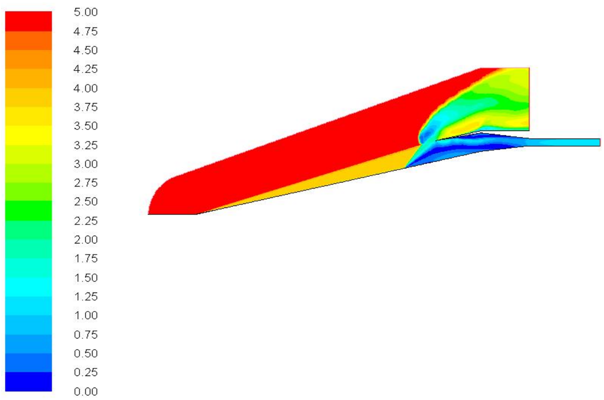

Figure 16 (b): Mach Number

Figure 16:2D Axisymmetric AR-2.5, M=5

CONCLUSIONS

In the current work, the starting problem has been studied for a hypersonic intake. Existence of the problem has been confirmed first by showing that the expected shock-structure cannot be obtained by simply accelerating the vehicle to the operating Mach number; i.e. by showing that the intake is not self-starting. As intake cowl is fixed for all the cases, the shock structure will remain same for particular Mach number. When the contraction ratio increases in 2-D planar from 1 to 2.5 the intake cowl reflected shock angle increases so that the high pressure zone will create that leads to the flow separation which in turn affects the intake starting. Whereas in axisymmetric for the same contraction ratio 1.7, the intake cowl reflected shock angle will not project as same as in 2-D planar, that's why, there will be no separation occurs in Axisymmetric condition.

For Height Ratio 1.7 symmetry condition, when the reflected shock hits to the bottom surface of the intake that will create a bubble. Based on the bubble size, the flow parameters like flow rate, total pressure and Mach number will change inside the intake. If the bubble size is large, then there will be gradual reduction of flow properties in the downstream. For symmetry case, height ratio 1.6 is the baseline to operate the intake without any disturbance in the flow but in terms of height ratio 1.7, we clearly observed that there is flow separate from the surface that may lead to intake unstart at designed condition. Whereas in axisymmetric condition even 1.7 also works without any flow disturbance and meets all designed requirements and thereafter the flow starts separating if the area ratio increases. So the baseline for the axisymmetric condition is 1.7 which is shown in results. Higher ratios might have worked, if we applied other applications like boundary bleeds, moveable cowl, changing altitude and etc.

During area ratio 2 and 2.5, we observed that the intake flow couldn't start in both condition. The high pressure zone created due to high contraction ratio that is not allowing to flow inside intake duct. High pressure region is observed and the flow get separated (due to adverse pressure gradient) from the surface that will lead to intake unstart.

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